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LOW TEMPERATURE THERMAL AND MECHANICAL PROPERTIES OF POLYSTYRENE AND POLYETHYLENE FOAMS †

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INTRODUCTION

The storage of cryogenic fluids in stationary and transport vessels demands a continual evaluation of thermal and mechanical properties of materials that are candidates for use as insulation materials.

This study presents an evaluation of several materials being considered for use in experimental cryogenic storage vessels at LLL. The materials studied were polystyrene and polyethylene foams of varying density. The properties measured were thermal contraction, thermal conductivity, and ultimate compressive and tensile strengths.

Experimental Apparatus and Procedure

Linear thermal contraction is measured utilizing a fused-silica dilatometer with a linear differential transducer as the dilatometer head. Great care is taken to insure that the fused silica pushrod and the sample tube are of the same material (i.e. same manufacturer, heat treatment, etc.). The LVDT is calibrated periodically to insure linearity and a run is often made with no specimen present to check the integrity of all mechanical couplings, etc., over the entire temperature range.

The sample tube and pushrod are housed in the sample space of a liquid helium throttling dewar, shown in Figure 1. This dewar is capable of attaining and controlling specimen temperature in the range 1.3 to 300 K. Thermocouples are generally mounted directly on the specimen and at regular intervals along the length and radius of the sample tube. A constant temperature region of about 10 inches along the length of the tube is achievable at any given throttle setting. Measurements are also taken to insure that the pushrod and sample tube temperatures are the same at any position along the length of the assembly.

Specimen length required is generally 2 inches, however, specimens as small as 5 mm have been successfully measured. Specimen diameter can be as high as 1/2 inch. The accuracy of a measurement on a 2-inch specimen is better than 1 percent. This is based on measurements of standard materials such as copper and nickel. The reproducibility of a given experiment over the entire range is about 6 to 10 microinches. The minimum detectable length change is 10^{-7} in/in. Figure 2 (a) is a schematic representation of the specimen assembly.

Thermal conductivity measurements were made on 1/4-in thick circular discs of foam material. A steady state method was used in which the foam specimen was bonded between a copper block heat sink and a thin walled, radially wound, copper heater. A bonding agent with a conductivity two orders of magnitude higher than the foams was used. The temperature gradient was measured with copper-constantan thermocouples attached at the bonded interfaces. A guard heater was mounted around the specimen assembly to minimize radial heat transfer. All leads were thermally anchored to a temperature controlled block. A correction for radiative heat transfer from one face of the gradient heater was made by calibrating the instrument without the sample present. All measurements were made in a vacuum of 10^{-6} mm Hg. A schematic of the specimen setup is shown in Fig. 2 (b).

Sample temperature was controlled with the use of throttling dewar, similar to that shown in Fig. 1, and an auxiliary temperature control system attached to the sample can. The temperature gradient (ΔT) was measured with a Keithley 147 nanovoltmeter.

The ultimate compressive foam strengths were measured in a compression tube cryostat shown schematically in Fig. 3. The specimens were all one inch diameter cylinders one inch high. For the tensile measurements, the specimens were bonded to slightly recessed copper end pieces with the aid of a bench-top alignment jig. The bonding agent was a Stycast epoxy resin. The compression tests were performed in a reversing cage with no bonding agent used. Temperature was controlled with the aid of the throttling dewar depicted in Fig. 3, and the temperature was measured with copper-constantan thermocouples mounted on the specimen holders. The strain rate used for all of the tests was 0.050 in/min.

Specimen Specifications

The beaded polystyrene foams were fabricated by Bendix Corporation, Kansas City Division for LLL. Two densities of the foam were evaluated, 0.05 gm/cc and 0.10 gm/cc. A typical analysis of this material is presented below:

Chemical Analysis

Element	Wt. %
C	91.88
H	7.95
Cl	7.5 ppm
Ash	88 ppm

The polyethylene foam evaluated was a modified Ethafoam 900, available commercially from Dow Chemical. The LLL requirement for this material was for polyethylene of density 0.22 gm/cc with a open cellular structure. This requirement was met by soaking Ethafoam 900 in dry ice until the material reaches equilibrium and then pressing blocks of the material to predetermined dimensions such that the density increased from the "as received" 0.144 gm/cc to 0.22 gm/cc.

An examination of the cell structure showed previously closed cells were ruptured by the compression at reduced temperature. A typical chemical and spectrographic analysis is presented below:

Chemical Analysis

Element	Wt. %
C	85.31
H	14.01
N	0.15
S	< .05
Cl	.22
(Ash)	.55

Spectrographic Analysis

Element	ppm
Al	10
Ca	1000
Cr	.5
Fe	8
Mn	.1
Na	12
Si	1500
Sr	12
Ti	2
Zn	3

The thermal property measurements were made on the material in two directions, since it was anticipated that the material may exhibit anisotropic properties caused by the restructuring of the material cells when it was compressed to increase the bulk density. The two directions measured are indicated as "vertical" and "horizontal" in this report.

The "vertical" direction is the direction in which compression was used to increase the density. The "horizontal" direction is perpendicular to the compression direction.

Experimental Results

All foam materials were stored in a dry environment until used. After being loaded into the experimental apparatus, the chambers containing the foam specimens were evacuated to 10^{-6} torr before the measurements were begun.

The thermal contraction results on both the polystyrene and polyethylene foams were shown in Figure 4. The results clearly indicate the anisotropic effects observed in the expansion behavior of polyethylene foam material. The material measured in the "vertical" direction has a considerable larger thermal contraction over the range from 4.2 to 300 K. The expansion behavior of the polystyrene foam materials appears to be nearly independent of density over the entire range of temperatures. The results obtained on each specimen are closely grouped and show no anomalous behavior.

Thermal conductivity measurements performed on polystyrene foams are shown in Figure 5. The results on the 0.1 g/cc material are about 40 percent higher in magnitude than those on the 0.05 g/cc material. The material was evacuated to 10^{-6} torr prior to beginning the test in order to reduce the effects of gas conduction. The shape of the curves is typical of insulating materials and the accuracy is considered to be 5 percent.

The thermal conductivity results on polyethylene foam in the horizonal and vertically directions as shown in Figure 6. It is seen from the results that the conductivity of the vertical direction is approximately twice that of the horizontal direction. The thermal expansion results also show gross differences between the two directions in that the vertical specimen contracts considerably more over the range of temperature than does the horizontal specimen. Attempts to relate conductivity and expansion data are difficult, however, one might conclude that the horizontal specimen contains foam cells which are less firmly attached to one another in the direction of measurement. As a result, the bulk expansion response is reduced and the thermal conductivity is lower.

The ultimate compressive and ultimate tensile strength results on polystyrene foam are shown in Figures 1 and 2. Compressive strength data show a consistent relationship with foam density, the more dense material being stronger. Temperature dependence is exhibited by material of either density, with strength being shown as a function of decreasing temperature. The tensile behavior of the foam materials studied is much less predictable. The strength-temperature dependence is considered to be the same as that observed in the compression testing, increasing strength with decreasing temperature. However, tests performed at 20 K did not clearly indicate this trend except on Samples 1-10 and 1-11. The other samples tested at 20K failed about 1/8 to 1/4 in. below the upper bonded interface and yielded considerably lower strength values. The distance from the upper bonded surface is considered sufficiently great to rule out bond failure. It is believed that stresses unaccounted for during the test caused this premature failure. These additional stresses probably arose as a result of improper cooldown procedures between room temperature and 20 K.

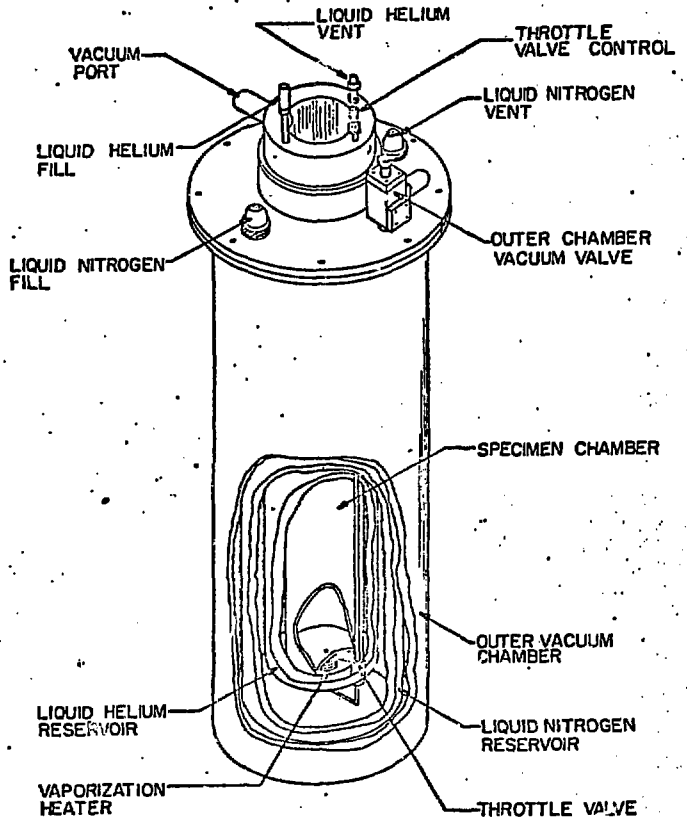


FIGURE 1. VARIABLE TEMPERATURE CRYOSTAT FOR THERMAL CONDUCTIVITY, THERMAL EXPANSION AND MECHANICAL STRENGTH MEASUREMENTS (1.2 - 300 K)

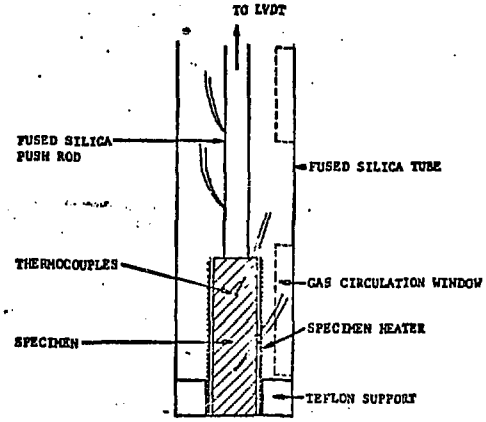


Fig. 2 (a). Specimen Arrangement in Fused Silica Dilatometer

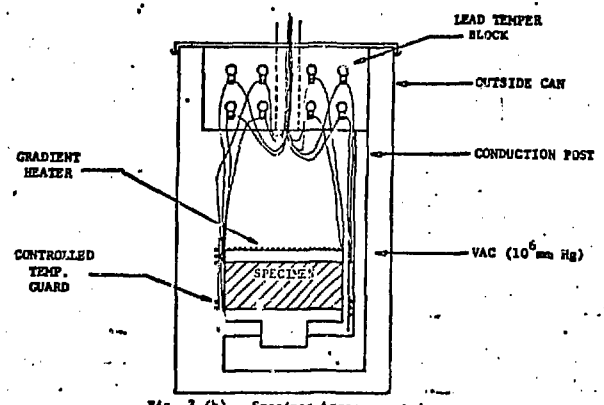


Fig. 2 (b). Specimen Arrangement in Thermal Conductivity Apparatus

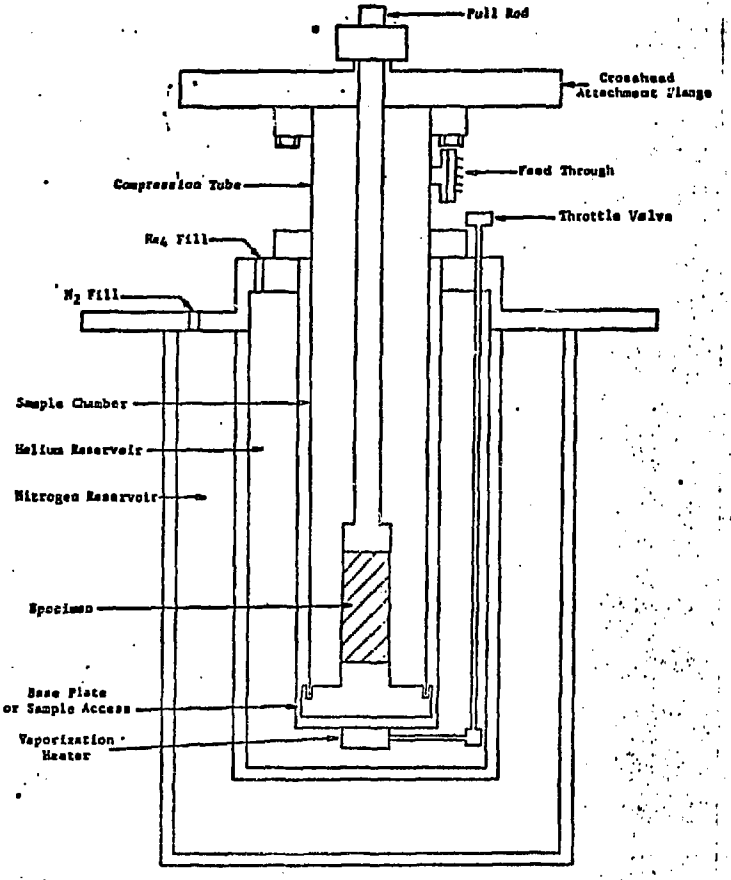


Fig. 3. 5000 lb load, compression tube cryostat.

TABLE 1. ULTIMATE COMPRESSIVE STRENGTH DATA FOR POLYSTYRENE FOAMS

Sample	Density, g/cc	Test Temperature, K	Spec. Diameter, in.	Spec. Length, in.	Area, $in.^2$	Load, lb	UCS, lb/in^2
3-3	0.0523	300	1.00	1.00	0.785	43	55
3-4	0.0529	300	1.00	1.00	0.785	51	65
3-5	0.0503	300	1.00	1.00	0.785	47	60
3-6	0.0513	300	1.00	1.00	0.785	47	60
6-1	0.1094	300	1.00	1.00	0.785	115	146
6-3	0.1092	300	1.00	1.00	0.785	121	154
6-4	0.1093	300	1.00	1.00	0.785	126	161
6-5	0.1095	300	1.00	1.00	0.785	109	140
3-9	0.0532	20	1.00	1.00	0.785	81	103
3-11	0.0514	20	1.00	1.00	0.785	92	117
1-5	0.0496	20	1.00	1.00	0.785	70	90
1-9	0.0508	20	1.00	1.00	0.785	76	97
6-8	0.0997	20	1.00	1.00	0.785	176	224
6-10	0.1017	20	1.00	1.00	0.785	188	239
4-7	0.0998	20	1.00	1.00	0.785	190	242
4-8	0.0983	20	1.00	1.00	0.785	200	255

TABLE 2. ULTIMATE TENSILE STRENGTH DATA FOR POLYSTYRENE FOAMS

Sample	Density, g/cc	Test Temperature, K	Spec. Diameter, in.	Spec. Length, in.	Area, $in.^2$	Load, lb	UTS, $lb/in.^2$
3-8	0.0515	300	1.00	1.00	0.785	99	126
3-11	0.0514	300	1.00	1.00	0.785	98	125
1-5	0.0496	300	1.00	1.00	0.785	99	126
1-9	0.0508	300	1.00	1.00	0.785	102	130
6-11	0.0998	300	1.00	1.00	0.785	160	204
6-12	0.1007	300	1.00	1.00	0.785	144	183
4-7	0.0998	300	1.00	1.00	0.785	176	224
4-8	0.0983	300	1.00	1.00	0.785	168	214
6-7	0.1010	77	1.00	1.00	0.785	186	237
3-12	0.0517	77	1.00	1.00	0.785	143	182
1-10	0.0512	20	1.00	1.00	0.785	287	366
1-11	0.0505	20	1.00	1.00	0.785	270	344

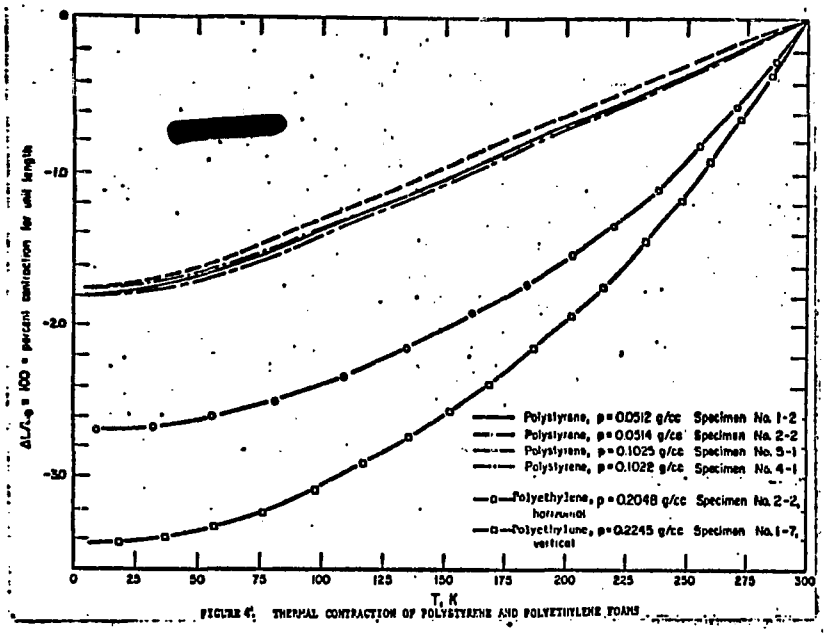
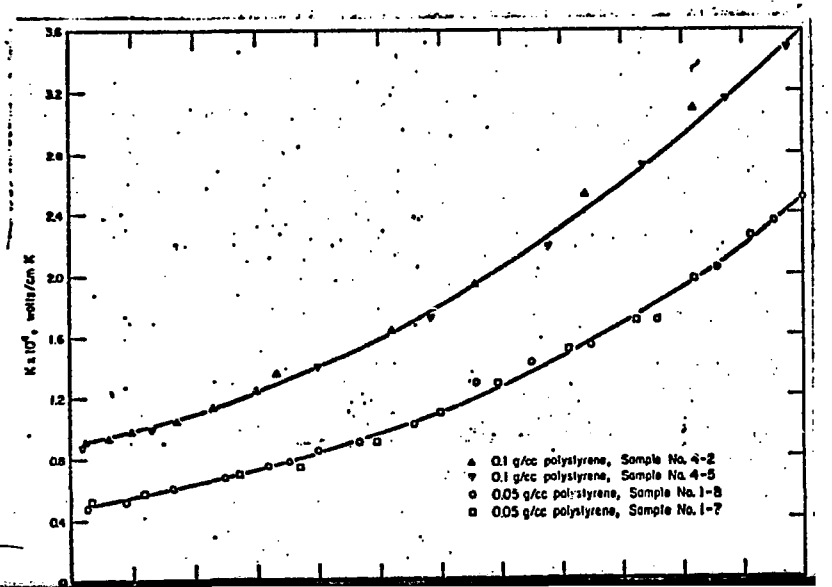


FIGURE 4. THERMAL CONTRACTION OF POLYSTYRENE AND POLYETHYLENE FOAMS



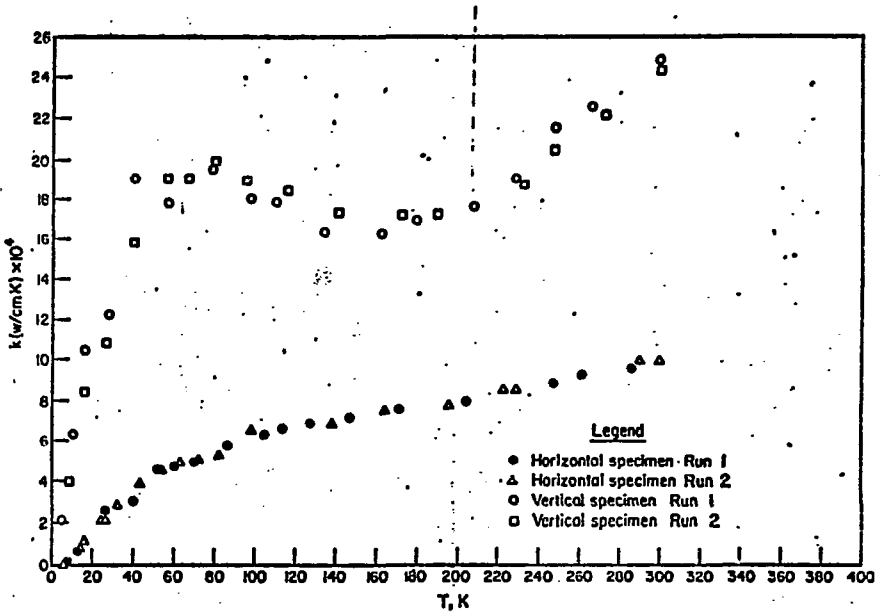
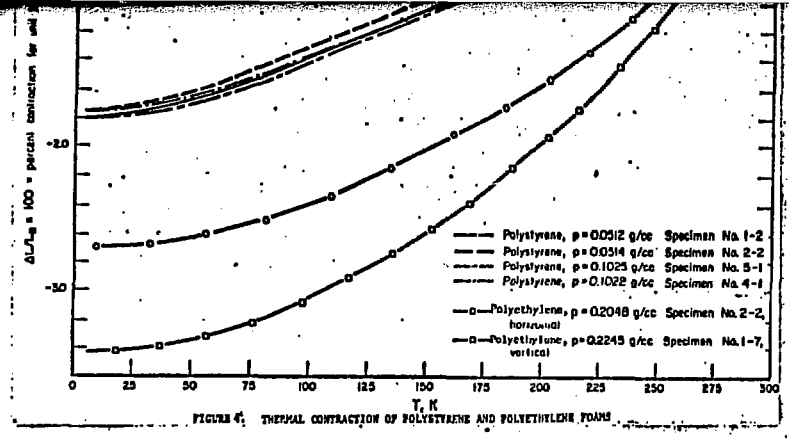


FIGURE 6. THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR POLYETHYLENE FOAM



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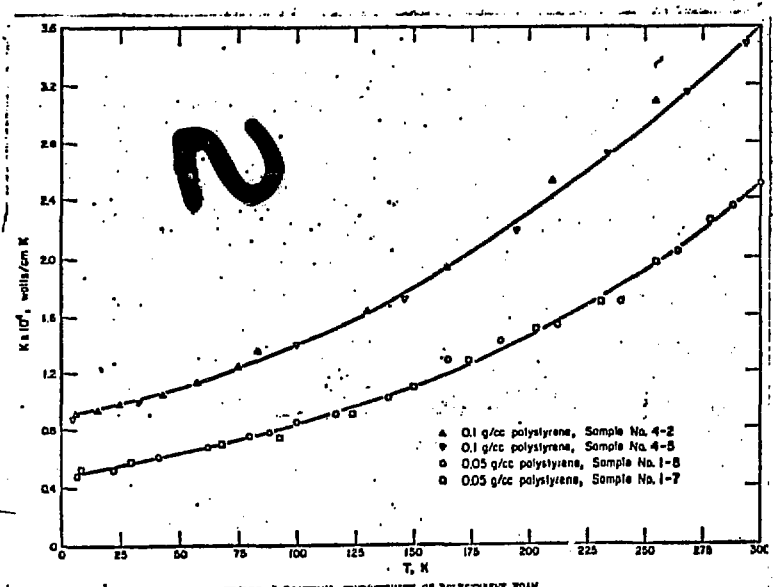

FIGURE 5 THERMAL CONDUCTIVITY OF POLYSTYRENE FOAM

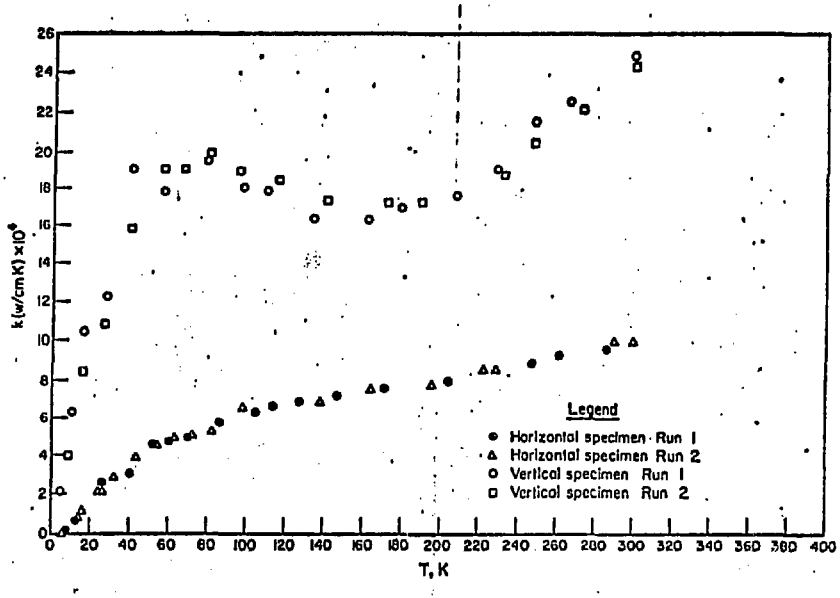

FIGURE 6. THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR POLYETHYLENE FOAM